5.3.4 Heat Capacity

Heat Capacity (HC) is used in energy codes to determine when a wall has enough thermal mass to use the mass criteria or mass credit. Heat capacity is the ability to store heat per unit area of wall area and includes all layers in a wall. For a single layer wall, HC is calculated by multiplying the density of the material by its thickness times the specific heat of the material. Heat capacity for a multilayered wall is the sum of the heat capacities for each layer. The heat capacity of non-concrete layers is generally small and can typically be ignored in calculations.

Specific heat describes a material's ability to store heat energy. As a material absorbs energy, its temperature rises. A material with a high specific heat, such as water, can absorb a great deal of heat energy per pound of material, with little rise in temperature. The same weight of a material with low specific heat, such as steel or copper, rises to higher temperatures with only a small quantity of heat absorbed. Because specific heat defines the relationship between heat energy and temperature for a given weight of material, it can also be used to determine the change in temperature for a material as it absorbs or releases energy. Specific heat is defined as the quantity of heat energy in Btus required to raise the temperature of one pound of a material by 1°F. The specific heat of concrete can generally be assumed to be 0.2 Btu/lb·°F. Specific heat of selected other materials is provided in Table 5.3.4.

Energy codes generally require a heat capacity greater than 6 Btu/ft^2·°F in order to use mass wall criteria. These criteria generally allow a lower wall R-value. The *ANSI/ASHRAE/IESNA Standard 90.1-2007* requires a heat capacity greater than 7 Btu/ft^2·°F, except lightweight concrete walls with a unit weight not greater than 120 pcf need only have a heat capacity of 5 Btu/ft^2·°F or greater. Table 5.3.9 provides heat capacities of concrete walls. These walls meet the minimum requirements for mass wall criteria in almost all cases.

5.3.5 Thermal Mass

The thermal mass provided by concrete buildings saves energy in many climates. Thermal mass shifts peak loads to a later time and reduces peak energy requirements for building operations. Laboratory, analytical, and field studies support this concept. Thermal resistance (R-values) and thermal transmittance (U-factors), discussed in Section 5.3.3, do not take into account the effects of thermal mass, and by themselves, are inadequate in describing the heat transfer properties of construction assemblies with significant amounts of thermal mass.

As previously discussed, common thermal properties of construction materials and air spaces are based on steady state tests, which measure the heat that passes from the warm side to the cool side of the test specimen. Thermal transmittance (U-factor) and its reciprocal, overall R-value is generally considered the most significant indication of heat gain because low mass buildings constructed of metal or wood frame have heat losses proportional to the overall area-weighted U-factor of the building envelope (walls and roof). Also, U-factors and R-values are relatively easy to calculate since they are based on steady-state conditions.

However, the steady-state condition is rarely realized in actual practice. External conditions (temperatures, position of the sun, presence of shadows, etc.) vary throughout a day, and heat gain is not instantaneous through most solid materials, resulting in the phenomenon of time lag (thermal inertia). As temperatures rise on one side of a wall, heat begins to flow toward the cooler side. Before heat transfer can be achieved, the wall must undergo a temperature increase. The thermal energy necessary to achieve this increase is related to heat capacity.

Due to its density, concrete has the capacity to absorb and store large quantities of heat. This thermal mass allows concrete to react very slowly to changes in outside temperature. This characteristic of thermal mass reduces peak heating and cooling loads and delays the time at which these peak loads occur by several hours (Fig. 5.3.17[a]). Mass effects vary with climate, building type, orientation, position of mass within the wall, and other factors, so quantifying their effects is more challenging than calculating R-values. Mass effect, glass area, air infiltration, ventilation, building orientation, exterior color, shading or reflections from adjacent structures, surrounding surfaces or vegetation, building shape, number of stories, wind direction, and speed all affect energy use.

Analytical and experimental studies have shown that the use of materials with thermal mass in buildings reduces heating and cooling peak loads, and thus reduces equipment size compared with buildings constructed with lightweight materials. Small HVAC equipment that runs continuously uses less energy than large equipment that is run intermittently as it responds to peak loads. By lowering peak loads, energy is saved. Peak cooling loads in office buildings are often in midafternoon. Properly designed thermal mass can shift a portion of the load and undesireable heat gain from midafternoon until later when the building is unoccupied or when peak load electricity costs are less. Also thermal mass on the interior building surface will help absorb heat gains in the office space.

Energy use differences between light and heavy materials are illustrated in the hour-by-hour computer analyses shown in Fig.

5.3.17. Fig. 5.3.17(a) compares the heat flow through three walls having the same U-factor, but made of different materials. The concrete wall consisted of a layer of insulation sandwiched between inner and outer wythes of 2 in. concrete with a combined weight of 48.3 psf. The metal wall, weighing 3.3 psf, had insulation sandwiched between an exterior metal panel and $^1/_2$ in. drywall. The wood frame wall weighed 7.0 psf and had wood siding on the outside, insulation between 2 × 4 studs, and $^1/_2$-in. drywall on the inside. The walls were exposed to simulated outside temperatures that represented a typical spring day in a moderate climate. The massive concrete wall had lower peak loads by about 13 percent for heating and 30 percent for cooling than the frame or non-mass walls. Actual results for buildings depend on the location, time of year, and building design.

Concrete walls of various thicknesses that were exposed to the same simulated outside temperatures are compared in Fig. 5.3.17(b). The walls had a layer of insulation sandwiched between concrete on the outside and $^1/_2$ in. drywall on the inside; U-factors were the same. The figure shows that the more massive the wall, the lower the peak loads and the more the peaks were delayed.

Fig. 5.3.17(c) compares concrete sandwich panels having an outer wythe of 2 in., various thicknesses of insulation, and various thicknesses of inner wythes. All walls had U-factors of 0.091 and were exposed to the same simulated outside temperatures. The figure shows that by increasing the thickness of the inner concrete wythe, peak loads were reduced and delayed.

ASHRAE Standard 90.1 acknowledges the thermal mass benefits of concrete walls in specifying lower minimum insulation R-value and higher maximum wall U-factors for mass (concrete) wall construction. For example, in a region with 5401-7200 heating degree days base 65°F (HDD65 [Chicago]), the minimum R-value for concrete wall insulation is R 7.6ci (ci = continuous insulation) and for steel framed walls the minimum R-value for the wall insulation is R 13 + R 3.8 ci. For the same region the maximum wall U-factor for concrete walls is 0.123 and for steel framed walls the maximum U-factor is 0.084.

In fact, research conducted by Oak Ridge National Laboratory (ORNL) on the computer modeling and simulation of dynamic thermal performance of insulated concrete walls versus traditional wood frame shows that insulated concrete sandwich walls constructed with composite connector technology utilizes the thermal mass effect of concrete to create an "equivalent wall performance R-value" several times greater than what is estimated by a traditional material R-value calculation.[1] In this study, six climates were evaluated – Atlanta, Denver, Miami, Minneapolis, Phoenix, and Washington, D.C. Of these cities, the difference was most dramatic in Phoenix, where a comparable R-value of conventional wood frame exterior wall would need to be 2.9 times higher than the steady state R-value of an insulated concrete sandwich panel wall to produce the same energy loads. Therefore a comparative wood frame wall R-value would need to have an R 31 to achieve the same effect as an R 11 insulated concrete sandwich panel wall constructed with composite connector technology.

Energy saving benefits of thermal mass are most pronounced when the outside temperature fluctuates above and below the balance temperature of the building, causing a reversal of heat flow within the wall. The balance point is generally between 50 and 70ºF, depending on the internal gains due to people, equipment and solar effects. These ideal conditions for thermal mass exist on a daily basis at all locations in the United States and Canada during at least some months of the year. Thermal mass is most effective in conserving energy in the sun-belt regions in the Southern and Western United States, because these daily temperature fluctuations occur throughout the year. Thermal mass also works well when daily temperatures have large variations between the daytime high and nighttime low and when outdoor air can be used for nighttime ventilation. These conditions are most prevalent in the western states. Designs employing thermal mass for energy conservation should be given a high priority in these areas.

Another factor affecting the behavior of thermal mass is the availability of internal heat gains. This includes heat generated inside the building by lights, equipment, appliances and people. It also includes heat from the sun entering through windows. Generally, during the heating season, benefits of thermal mass increase with the availability of internal heat gains; Tables 5.3.10(a) and 5.3.10(b) may be used as a guide. Thus, office buildings which have high internal heat gains from lights, people, and large glass areas represent an ideal application for thermal mass designs. This is especially true if the glass has been located to take maximum advantage of the sun. During the cooling season, thermal mass "coupled" or exposed to the building occupied spaces will absorb internal gains, thereby shifting the peak cooling periods. Concrete exposed to the interior and not covered by insulation and gypsum wallboard is best able to absorb internal gains, thereby saving cooling energy.

The first phase of a botanical center used the high mass characteristics of precast concrete to store heat and stabilize temperatures (Fig. 5.3.18). The walls consist of 12-in. sandwich panels having a 3-in. outer wythe, 3 in. of insulation, and a 6 in. inner wythe resulting in an R-value of 16. The inside 6 inch layer of concrete provided approximately 480,000 pounds of mass for storage of passive solar heat. The high mass radiates heat back into the structure in the late afternoon and evening. Precast concrete was also used for its light color and its ability to reflect sunlight into the garden area.

1 *"Thermal Performance of Prefabricated Concrete Sandwich Wall Panels,"* J. Kosny, P. Childs and A. Desjarlais, Oak Ridge National Laboratory Buildings Technology Center, October 2001

Only computer programs such as DOE-2[2], Energy-10[3], and EnergyPlus[4] that take into account *hourly* heat transfer on an annual basis (8760 hours) are adequate in determining energy loss in buildings with mass walls and roofs.

Building codes and standards provide prescriptive and performance paths for meeting requirements using thermal mass. Prescriptive paths have required minimum or maximum values in easy-to-use tables for each building component. Generally, R-value requirements for mass walls are less than those for wood or steel frame walls. To obtain a range of R-values, the precast concrete walls may have insulation applied to the interior or the insulation may be fully incorporated into a sandwich wall panel.

Performance paths are used to trade one energy saving measure for another. For instance, if the wall insulation does not meet the prescriptive requirements, but the ceiling insulation exceeds the prescriptive requirements, then using a performance method may show compliance of the whole building with the code. Prescriptive paths are commonly used for typical buildings in states with newly adopted codes. Once designers become familiar with performance software, these become more popular. Some performance methods can be used to show energy savings beyond code, and are used for sustainability programs or state tax credits.

The performance paths in energy codes generally allow the use of an easy-to-use computer trade-off program or a detailed energy budget method. Generally the more complicated the compliance tool, the more flexibility the designer is allowed. Trade-off tools also allow for innovation in design and materials. ENVSTD is an easy-to-use program for determining compliance of the building envelope of commercial buildings with ASHRAE 90.1. COMcheck-EZ™ (www.EnergyCodes.gov) is an easy-to-use program for determining commercial building compliance for ASHRAE 90.1, IECC (www.IccSafe.org) and many state codes.

COMcheck-Plus™ is a more detailed program using the whole building approach to determine compliance. This program is useful when buildings have special features such as large skylight areas. A detailed computer-based energy analysis program such as DOE2 or Energy Plus calculate yearly energy consumption for a building on an hourly basis. Such programs are useful when using the energy budget method because other simpler compliance tools do not take into account special features of the building or its components. The energy budget method compares the annual energy use of a building that meets prescriptive requirements with the proposed building to determine compliance. Codes provide rules and guidelines for the energy budget method. All of these performance path methods incorporate thermal mass effects.

Energy codes often specify insulation requirements for mass walls based on whether the insulation is on the interior of the wall, integral or on the exterior. Interior insulation isolates the mass from the interior, reducing the ability of the thermal mass to moderate the indoor temperature. Integral insulation refers to thermal mass on both sides of the insulation, as with an insulated sandwich panel wall. It should be noted that regardless of insulation placement, insulated mass walls combine the benefits of insulation and mass and are often quite energy efficient.

2 DOE-2 http://simulationresearch.LBL.gov
3 Energy-10, www.sbicouncil.org
4 Energy Plus, www.energyplus.gov.

Table 5.3.8 Effective R-Values for Walls with Insulation in Cavity between Metal Furring or Studs[1].

Depth of framing and cavity, (in.)	Rated R-value of insulation												
	0	1	2	3	4	5	6	7	8	9	10	11	12
	Effective R-value if continuous insulation uninterrupted by framing (includes gypsum board)												
	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
	Effective R-value if insulation is installed in cavity between metal framing (includes gypsum board)												
0.5	0.9	0.9	1.1	1.1	1.2	na	na	na	na	na	na	na	na
0.8	1	1	1.3	1.4	1.5	1.5	1.6	na	na	na	na	na	na
1.0	1	1.1	1.4	1.6	1.7	1.8	1.8	1.9	1.9	na	na	na	na
1.5	1.1	1.2	1.6	1.9	2.1	2.2	2.3	2.4	2.5	2.5	2.6	2.6	2.7
2.0	1.1	1.2	1.7	2.1	2.3	2.5	2.7	2.8	2.9	3	3.1	3.2	3.2
2.5	1.2	1.3	1.8	2.3	2.6	2.8	3	3.2	3.3	3.5	3.6	3.6	3.7
3.0	1.2	1.3	1.9	2.4	2.8	3.1	3.3	3.5	3.7	3.8	4	4.1	4.2
3.5	1.2	1.3	2	2.5	2.9	3.2	3.5	3.8	4	4.2	4.3	4.5	4.6
4.0	1.2	1.3	2	2.6	3	3.4	3.7	4	4.2	4.5	4.6	4.8	5
4.5	1.2	1.3	2.1	2.6	3.1	3.5	3.9	4.2	4.5	4.7	4.9	5.1	5.3
5.0	1.2	1.4	2.1	2.7	3.2	3.7	4.1	4.4	4.7	5	5.2	5.4	5.6
5.5	1.3	1.4	2.1	2.8	3.3	3.8	4.2	4.6	4.9	5.2	5.4	5.7	5.9

Depth of framing and cavity, (in.)	Rated R-value of insulation												
	13	14	15	16	17	18	19	20	21	22	23	24	25
	Effective R-value if continuous insulation uninterrupted by framing (includes gypsum board)												
	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	22.5	23.5	24.5	25.5
	Effective R-value if insulation is installed in cavity between metal framing (includes gypsum board)												
0.5	na	na	na	na	na	na	na	na	na	na	na	na	na
0.8	na	na	na	na	na	na	na	na	na	na	na	na	na
1.0	na	na	na	na	na	na	na	na	na	na	na	na	na
1.5	na	na	na	na	na	na	na	na	na	na	na	na	na
2.0	3.3	3.3	3.4	3.4	na	na	na	na	na	na	na	na	na
2.5	3.8	3.9	3.9	4	4	4.1	4.1	4.1	na	na	na	na	na
3.0	4.3	4.4	4.4	4.5	4.6	4.6	4.7	4.7	4.8	na	na	na	na
3.5	4.7	4.8	4.9	5	5.1	5.1	5.2	5.2	5.3	5.4	5.4	5.4	5.5
4.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.8	5.9	5.9	6	6
4.5	5.4	5.6	5.7	5.8	5.9	6	6.1	6.2	6.3	6.4	6.4	6.5	6.6
5.0	5.8	5.9	6.1	6.2	6.3	6.5	6.6	6.7	6.8	6.8	6.9	7	7.1
5.5	6.1	6.3	6.4	6.6	6.7	6.8	7	7.1	7.2	7.3	7.4	7.5	7.6

1 ASHRAE 90.1-2007, www.ASHRAE.org

Table 5.3.9 Heat Capacity of Concrete.

Concrete Thickness, in.	Heat Capacity, Btu/ft²·°F	
	145 pcf	110 pcf
3	7.2	5.5
4	9.6	7.3
5	12.0	9.2
6	14.4	11.0
7	16.8	12.8
8	19.2	14.6
9	21.6	16.5
10	24.0	18.3
11	26.4	20.2
12	28.8	22.0

ASHRAE 90.1-2007, www.ASHRAE.org

Fig. 5.3.17(a-c) Heating and cooling load comparisons.

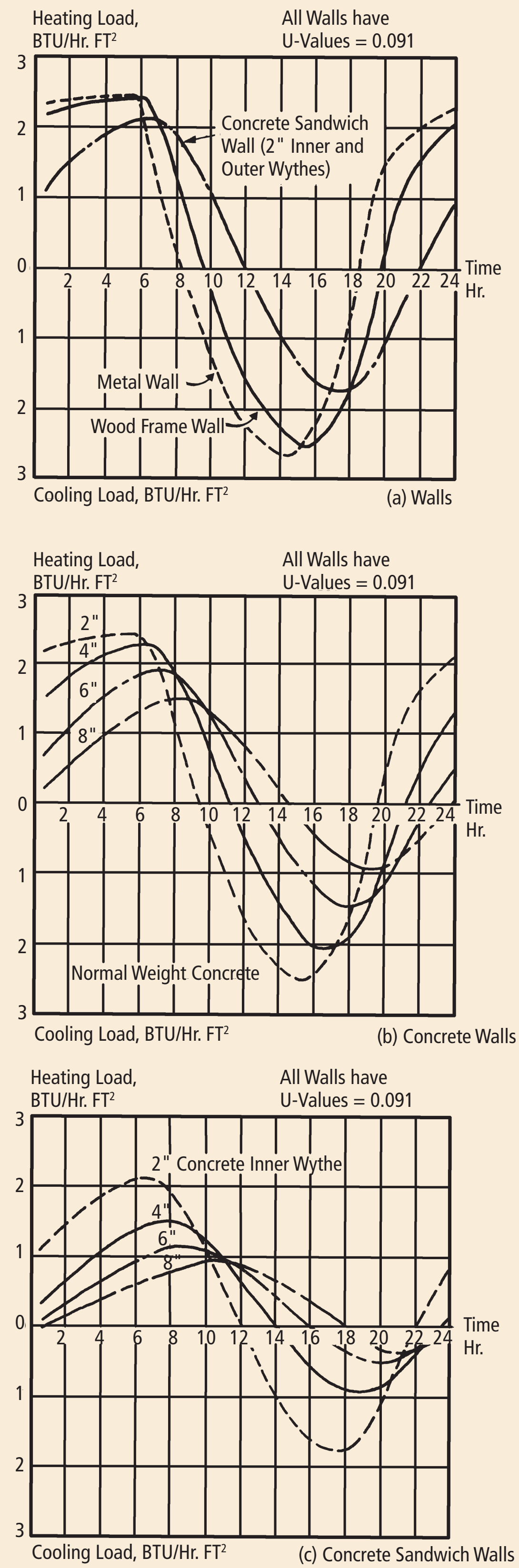

Table 5.3.10 (a) Design Considerations for Building with High Internal Heat Gains[1].

Climate Classification		Relative Importance of Design Considerations[2]						
		Thermal Mass	Increase Insulation	External Fins[3]	Surface Color: Light	Surface Color: Dark	Daylighting	Reduce Infiltration
Winter								
Long heating season (6000 degree days or more)	With sun and wind[4,5]	1	2	2		2	3	3
	With sun without wind	1	2			2	3	3
	Without sun and wind		2			1	3	3
	Without sun with wind	1	2	2		1	3	3
Moderate heating season (3000–6000 degree days)	With sun and wind	2	2	1		1	2	2
	With sun without wind	2	2			1	2	2
	Without sun and wind	1	2				2	2
	Without sun with wind	1	2	1			2	2
Short heating season (3000 degree days or less)	With sun and wind	3	1				1	1
	With sun without wind	3	1				1	1
	Without sun and wind	2	1				1	1
	Without sun with wind	2	1				1	1
Summer								
Long cooling season (1500 hr. at 80 °F)	Dry or humid	3		3	3		2	3
Moderate cooling season (600–1500 hr. at 80 °F)	Dry or humid	3		2	2		2	3
Short cooling season (Less than 600 hr. 80 °F)	Dry or humid	2		1	1		2	3

1 Includes office buildings, factories, and commercial buildings.

2 Higher numbers indicate greater importance.

3 Provide shading and protection from direct wind.

4 With sun: sunshine during at least 60% of daylight time.

5 With wind: average wind velocity over 9 mph.

IMPORTANCE RATING KEY
3 High
2 Medium
1 Low

Table 5.3.10 (b) Design Considerations for Building with Low Internal Heat Gains[1].

Climate Classification		Relative Importance of Design Considerations[2]					
		Thermal Mass	Increase Insulation	External Fins[3]	Surface Color: Light	Surface Color: Dark	Reduce Infiltration
Winter							
Long heating season (6000 degree days or more)	With sun and wind[4,5]		3	2		3	3
	With sun without wind		3			3	3
	Without sun and wind		3			2	3
	Without sun with wind		3	2		2	3
Moderate heating season (3000–6000 degree days)	With sun and wind	1	2	1		2	3
	With sun without wind	1	2			2	3
	Without sun and wind		2			1	3
	Without sun with wind	1	2	1		1	3
Short heating season (3000 degree days or less)	With sun and wind	2	1			1	2
	With sun without wind	2	1			1	2
	Without sun and wind	1	1				2
	Without sun with wind	1	1				2
Summer							
Long cooling season (1500 hr. at 80 °F)	Dry[6] or humid[7]	3		2	2		3
Moderate cooling season (600–1500 hr. at 80 °F)	Dry	2		1	1		2
	Humid	2		1	1		3
Short cooling season (less than 600 hr. at 80 °F)	Dry or humid	1					1

1 Includes low-rise residential buildings and some warehouses.

2 Higher numbers indicate greater importance.

3 Provide shading and protection from direct wind.

4 With sun: sunshine during at least 60% of daylight time.

5 With wind: average wind velocity over 9 mph.

6 Dry: daily average relative humidity less than 60% during summer.

7 Humid: daily average relative humidity greater than 60% during summer.

IMPORTANCE RATING KEY
3 High
2 Medium
1 Low

Fig. 5.3.18
Quad City Botanical Center, Rock Island, Illinois; Architect: Change-Environmental Architecture; Photo: Dale Photographics, Inc.